

5 **SYSTEMS, METHODS AND COMPUTER PROGRAM PRODUCTS FOR
ENCRIPTION AND DECRYPTION USING WAVELET TRANSFORMS**

RELATED APPLICATION DATA

 The present invention claims the benefit of U.S. Provisional Patent
10 Application Serial No. 60/398,506, filed July 25, 2002, titled "System and Method
for Enabling Efficient Encryption and Decryption Using Wavelet Transforms Over
Finite Fields," the contents of which are hereby incorporated by reference as if set
fully herein.

15 **FIELD OF THE INVENTION**

 The present invention relates generally to systems, methods and computer
program products for encryption and decryption. More particularly, the invention
relates to systems, methods and computer program products for encrypting and
decrypting data using wavelet transforms over finite fields to ensure security of the
20 data during transmission.

BACKGROUND OF THE INVENTION

 The advancement of technology has led to an increasing demand for
efficient and reliable data transmission and storage systems. This demand has led
25 to the creation of new methods of data encryption for data storage and data
transmission over physical channels.

For instance, cellular transmissions have been historically insecure and virtually anyone can intercept virtually any cellular transmission or conversation. Future mobile phones will play a pivotal role in electronic-business by delivering a range of services anywhere, and at any time. Therefore, in the event hackers could
5 intercept such services, serious fraud could result. As a result, security technologies will be critical for building user confidence and facilitating broad market adoption of next-generation wireless e-business solutions.

Thus far, many encryption techniques have been created to reduce the likelihood of a successful communication interception. Nevertheless, virtually all
10 encryption methods cannot prevent all interceptions. What is therefore needed are effective and reliable systems and methods for encryption and decryption.

SUMMARY OF THE INVENTION

Filter banks and wavelet transforms have established themselves as
15 powerful tools in the analysis of signals and images when these objects are viewed as sequences over real or complex fields. The present invention extends wavelet transforms to finite fields replacing the complex field, which provides an effective method for securing communications through encryption and decryption. The present invention may also be applied to other cryptographic uses, such as
20 signatures and authentication.

According to one embodiment of the present invention, systems, methods, and computer program products of the present invention provide encryption and decryption using wavelet transforms over finite fields. Specifically, the wavelet encryption system and wavelet decryption system (collectively, the “wavelet
25 cryptosystem”) includes one or more filters that receive a set of wavelet coefficients as input. The wavelet coefficients are then utilized by the wavelet

encryption system to cause the filters to convert plaintext in cyphertext (i.e., the encrypted version of the plaintext). The cyphertext is then decrypted by the wavelet decryption system, which is operable to reconstruct the original plaintext using wavelet transforms that reverse the effect of the wavelet encryption system.

- 5 Like the encryption, the decryption of the cyphertext depends on wavelet coefficients which permit the decryption system to cause filters to transform the cyphertext into the plaintext.

It will be appreciated that the abovementioned coefficients are derived by utilizing a series of mathematical relational equations. More specifically, the
10 present invention provides for a general wavelet decomposition of sequences defined over finite fields. The performance of mathematical operations and supplying of filter coefficients for filters implementing encoding and decoding within the cryptosystem of the present invention may be accomplished by utilizing hardware, software, firmware, or a combination thereof.

- 15 According to the present invention, two methods of generating filter coefficients are provided, thus creating two separate methods for generating the shared key used by the transmitting device and receiving device for encrypting and decrypting a communication transmitted over a communications medium.

20 BRIEF DESCRIPTION OF THE DRAWINGS

Having thus described the invention in general terms, reference will now be made to the accompanying drawings, which are not necessarily drawn to scale, and wherein:

- FIG. 1 shows a block diagram system of the present invention, according to
25 one embodiment of the present invention.

FIG. 2 shows an analysis bank and synthesis bank for effecting encryption and decryption, according to one embodiment of the present invention.

FIG. 3A shows an elementary transform block used for encryption, according to one embodiment of the present invention.

5 FIG. 3B shows a polyphase representation of the elementary transform block of FIG. 3A, according to one embodiment of the present invention.

FIG. 4A shows an elementary inverse transform block used for decryption, according to one embodiment of the present invention.

10 FIG. 4B shows a polyphase representation of the elementary inverse transform block of FIG. 4A, according to one embodiment of the present invention.

FIG. 5A shows an elementary nonlinear transform block used for the encryption, according to one embodiment of the present invention.

FIG. 5B shows an elementary nonlinear inverse transform block used for the decryption, according to one embodiment of the present invention.

15 FIG. 6A shows the wavelet encryption system according to one embodiment of the present invention.

FIG. 6B shows the wavelet decryption system according to one embodiment of the present invention.

20 FIG. 7A shows the nonlinear transform block constructed by exchanging the rule of the wavelet transform with that of the inverse wavelet in FIG. 5A, according to one aspect of the present invention.

FIG. 7B shows the inverse transform blocks constructed by exchanging the rule of the wavelet transform with that of the inverse wavelet in FIG. 5B, according to one aspect of the present invention.

FIG. 8 shows an M -channel maximally decimated filter bank, according to one embodiment of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

5 The present invention now will be described more fully hereinafter with reference to the accompanying drawings, in which preferred embodiments of the invention are shown. This invention may, however, be embodied in many different forms and should not be construed as limited to the embodiments set forth herein; rather, these embodiments are provided so that this disclosure will be thorough and
10 complete, and will fully convey the scope of the invention to those skilled in the art. Like numbers refer to like elements throughout.

It will be appreciated that the systems and methods of the present invention are described below with reference to block diagrams and flowchart illustrations. It should be understood that blocks of the block diagrams and flowchart illustrations,
15 and combinations of blocks in the block diagrams and flowchart illustrations, respectively, may be implemented by computer program instructions. These computer program instructions may be loaded onto a general purpose computer, special purpose computer, or other programmable data processing apparatus to produce a mechanism, such that the instructions which execute on the computer or
20 other programmable data processing apparatus create means for implementing the functions specified in the flowchart block or blocks.

These computer program instructions may also be stored in a computer-readable memory that can direct a computer or other programmable data processing apparatus to function in a particular manner, such that the instructions stored in the
25 computer-readable memory produce an article of manufacture including instruction

means that implement the functions specified herein. The computer program instructions may also be loaded onto a computer or other programmable data processing apparatus to cause a series of operational steps to be performed on the computer or other programmable apparatus to produce a computer implemented
 5 process such that the instructions that execute on the computer or other programmable apparatus provide steps for implementing the functions specified herein.

Accordingly, blocks of the block diagrams and flowchart illustrations support combinations of means for performing the specified functions,
 10 combinations of steps for performing the specified functions and program instruction means for performing the specified functions. It will also be understood that each block of the block diagrams and flowchart illustrations, and combinations of blocks in the block diagrams and flowchart illustrations, can be implemented by special purpose hardware-based computer systems that perform the specified
 15 functions or steps, or combinations of special purpose hardware and computer instructions.

Referring now to FIG. 1, the system **5** of the present invention includes an information source **10**, which may be a person, or a machine such as a computer, that outputs message data **11** to be communicated to a receiving device **30** by a
 20 transmitting device **15** in communication therewith. The transmitting device **15** and receiving device **30** are in communication via a communication medium **20**. The devices **15**, **30** may comprise wireless devices, such as mobile phones or personal digital assistants (PDAs), or wired devices such as telephones or computers. The communication medium **20** include one or more communication
 25 pathways, and may include one or more networks **21**, such as wireless networks, public switch telephone offices, the Internet, microwave links, satellite links, and

high-frequency radio links or similar networks or network devices for facilitating the communication between the two devices **15, 30**.

To effect the communication from the information source **10** to the receiving device **30**, the message data **11** is transmitted by the information source **10** to the transmission device **15**, which is in communication therewith. More particularly, the message data **11** is transmitted to the source encoder **12** within the transmission device **15**. The message data **11** may be either a continuous waveform, e.g., analog speech, or a sequence of discrete symbols. Upon receiving the message data **11**, the source encoder **12** transforms the message data **11** into a sequence of binary digits referred to as an plaintext, as is known to one of reasonable skill in the art. The plaintext is in a finite field, and may include a relatively small field such that the sequence is 1s and 0s, or a larger field such that the sequence includes numbers between 0 and 255.

After its transformation into an plaintext, the plaintext is encrypted by the wavelet encryption system **13**, which is in communication with the source encoder **12**. The encrypted plaintext is referred to hereinafter as cyphertext. The wavelet encryption system **13** encrypts the plaintext to ensure that it remains secure during its transmission to the receiving device **30**. The wavelet encryption system **13** may also include and/or operate as a channel encoder such that the cyphertext is transformed into a discrete encoded sequence, or a code word. Because discrete symbols may not be suitable for transmission over a communication channel **20**, the code word may first be transmitted to a modulator **14** that transforms each output symbol into a waveform which is suitable for transmission over the communication channel **20**. Although the cyphertext transmitted from the transmitting device **15** to the receiving device **30** may include modulated

cyphertext, due to its modulation by the modulator **14**, the present invention will be described with reference hereafter to cyphertext.

According to one aspect of the present invention, although the source encoder **12**, wavelet encryption system **13** and modulator **14** are illustrated as separate components within the transmitting device **15**, it will be appreciated that the components may be combined. For example, according to one aspect of the present invention, the source encoder **12** and modulator **14** may be included within the wavelet encryption system **13**. According to another aspect of the present invention, one or more of the components **12**, **13**, **14** may also be in remote communication with the transmitting device **15** such that each component **12**, **13**, **14** need not reside within the device **15**. For example, the source encoder **12** may reside within the information source **10**. Additionally, as mentioned above, each of the components **12**, **13**, **14** may be implemented by hardware, software, or a combination thereof. According to a preferred embodiment of the present invention, the components **12**, **13**, **14** are implemented using a single digital signal processing chip located within the transmitting device.

After the cyphertext (which, as noted above may include modulated cyphertext) is transmitted across the communication channel **20**, the cyphertext may be processed by a demodulator **22** capable of producing a discrete or continuous output. Because the cyphertext sequence resulting from the demodulation may contain errors introduced by the physical channel (or storage medium) **20** one or more methods known to those of skill in the art may be used to reduce or eliminate such errors. The cyphertext outputted by the demodulator **22** is then transmitted to the wavelet decryption system **26**, which is operable to reconstruct the plaintext from the received cyphertext. According to one aspect of the present invention, the wavelet decryption system **26** may include a channel

decoder located therein to collect errors and reconstruct the original plaintext.

After decryption, the plaintext may be transmitted to a source decoder **28** which reverses the effects of the source encoder **12** by transforming the plaintext into the message data **11** transmitted by the information source **10**. According to a

5 preferred embodiment of the present invention, the components **22, 26, 28** are implemented using a single digital signal processing chip located within the receiving device **30**.

According to one embodiment of the present invention, systems and methods of the present invention provide encryption and decryption using wavelet
10 transforms over finite fields. Specifically, the wavelet encryption system **13** includes one or more filters that receives as input a set of wavelet coefficients. The wavelet coefficients are then utilized by the wavelet encryption system **13** to cause the filters to transform an plaintext into an cyphertext. The cyphertext is then decrypted by the wavelet decryption system **26**, which is operable to reconstruct the
15 original message data using inverse wavelet transforms that reverse the effect of the encryption system **13**. Like the encryption, the decryption of the encrypted sequence depends on wavelet coefficients which permit the decryption system **26** to cause filters to transform the cyphertext into plaintext, which may be decoded to produce the original message data **11**.

20 It will be appreciated that the abovementioned wavelets are derived by utilizing a series of mathematical relational equations. More specifically, the present invention provides for a general wavelet decomposition of sequences defined over finite fields. The performance of mathematical operations and supplying of filter coefficients for the encoding and decoding filters within the
25 wavelet encryption and decryption systems **13, 26** of the present invention may be accomplished by utilizing hardware, software, firmware, or a combination thereof.

Therefore, according to one aspect of the present invention, the coefficients are calculated by hardware and/or software operating on the transmitting device. The function of the wavelets and their significance in the systems and methods of the present invention are considered in detail with respect to FIGS. 2-8.

5 It should be appreciated that throughout the embodiments of the invention described herein all arithmetic is carried out in a specific finite field, $GF(p^r)$, where GF denotes a Galois field, p is a prime number and r relates to the type of finite field represented. As an example, if the desired field of use is the binary field, the specific finite field will be $GF(2)$. In such an embodiment the wavelet encryption
10 system **13** receives a series of 1s and 0s which are encrypted using wavelets. Furthermore, the description of the embodiments of the invention concerning the wavelet encryption system **13** and wavelet decryption system **26** are described with reference to block cipher or stream cipher, as will be appreciated by those of skill in the art. Briefly, block cipher may encrypt individual blocks of bits to be
15 transmitted by the transmitting device **15** to the receiving device **30**, whereas stream cipher will encrypt the entire stream of bits.

Next, as is shown in FIG. 2, the wavelet cryptosystem of the present invention may be implemented using an L -band analysis-synthesis filter bank **34**. For simplicity, the cryptosystem of the present invention is described using a two-
20 band wavelet. In particular, FIG. 2 shows analysis and synthesis banks **35**, **40** of a two-channel perfect reconstruction filter bank **34** in which the synthesis filters $g_0(n)$ and $g_1(n)$ are the scaling sequence and mother wavelet of lengths $(2N + 2)$, respectively.

According to one aspect of the invention, the analysis bank **35** performs the
25 wavelet transform and the synthesis bank **40** performs the inverse wavelet transform. Therefore, the filter bank **34** represent filters operable to encrypt

plaintext and to decrypt cyphertext using waveform and inverse waveform transforms. According to a preferred embodiment of the present invention, the wavelet transform is used for decryption and the inverse wavelet transform is used for encryption. This embodiment will be used hereinafter to describe the systems and methods of the present invention. However, according to another aspect of the invention, the wavelet transform may be used for encryption and the inverse wavelet transform may be used for decryption.

The analysis bank 35 performs the wavelet transform and the synthesis bank 40 performs the inverse wavelet transform. The boxes labeled $h_0(n)$, $h_1(n)$, $g_0(n)$, and $g_1(n)$ are digital filters (in the finite field) that perform convolution. The blocks labeled $\downarrow 2$ downsample the input plaintext $x(n)$ by a factor of two by taking every other sample, and those labeled $\uparrow 2$ increase the sampling rate by a factor of two by inserting one sample with value zero between each pair of samples of its input.

The sequences labeled $y_0(n)$, $y_1(n)$ are the wavelet coefficients. It will be appreciated that the impulse responses of the digital filters $h_0(n)$, $h_1(n)$, $g_0(n)$, and $g_1(n)$ must be related if the synthesis bank 40 is to invert the results of the analysis bank 35. This relation is specified by the wavelet basis functions. It will be appreciated by those of ordinary skill in the art that the analysis filters are derived from the synthesis filters using :

$$h_j((n))_{2N+2} = g_j((-n))_{2N+2} \quad j = 0,1 \quad n = 0, \dots, 2N+1,$$

where $(())_{2N+2}$ denotes a circular convolution of length $(2N + 2)$. The above relation is accurate for a block cipher where the convolution is cyclic. For the stream cipher case the relation is given by

$$h_j(n) = g_j(2N+2-n) \quad j = 0,1 \quad n = 0, \dots, 2N+2.$$

Additionally, for both stream cipher and block cipher $g_1(n)=g_0(2N+1-n)$ where $n = 0,1,\dots,2N+1$.

The basic operation of the filters $h_0(n)$, $h_1(n)$, $g_0(n)$, and $g_1(n)$ in FIG. 2 is convolution, i.e, a sum of products, in which the multiplications and additions are performed in the appropriate field. For certain applications, such as implementing block ciphers, the convolutions may be cyclic (or in signal processing terminology circular or periodic) and for others, such as stream cipher, they may be noncyclic (or ordinary linear) convolutions.

Generally stated, it is complex to find filter pairs of FIG. 2 that satisfy the perfect reconstruction property (i.e., where the synthesis bank **40** inverts the results of the analysis bank **35**) in a finite field. For a given length $2N + 2$, there might exist several solutions having different properties. As explained in detail hereinafter, the present invention provides two different methods for calculating the filter coefficients that can be used to generate filters used in the wavelet encryption and decryption systems **13**, **26** of the present invention to encrypt and decrypt data.

It will be appreciated that without the derivation of appropriate filter coefficients to perform the encryption and decryption, cyphertext will not be able to be reconstructed by the wavelet decryption system **26** because the filter coefficients represent a shared key used by the transmitting device and the receiving device to encrypt plaintext and decrypt cyphertext.

Filter Derivation Method One

According to one aspect of the present invention, to derive the filter coefficients $g_0(n)$, $g_1(n)$, $h_0(n)$ and $h_1(n)$ the relational equation $x(n) = \sum \langle \theta_k(n), x(n) \rangle \theta_k(n)$ is used, where $\theta_k(n)$ represents a basis function, and the inner product of $\langle \theta_k(n), x(n) \rangle$ is used to derive the wavelet coefficients of the basis

function. The inverse wavelet representation of this relational equation, with relation to FIG. 2, namely

$$c(n) = \sum_{j \in \mathbb{Z}} \langle g_0(n-2j), c(n) \rangle g_0(n-2j) + \sum_{j \in \mathbb{Z}} \langle g_1(n-2j), c(n) \rangle g_1(n-2j)$$
 is then taken,

wherein the two functions $g_0(n)$ and $g_1(n)$ relate to the scaling function and mother wavelet respectively. In this equation, the inner product of $\langle g_0(n-2j), c(n) \rangle$ is representative of the wavelet coefficient $x_0(n)$ of FIG. 3, considered further below, and the inner product of $\langle g_1(n-2j), c(n) \rangle$ is representative of the wavelet coefficient $x_1(n)$ of FIG. 3. Therefore, $c(n)$ can be represented by the equation:

$$c(n) = \sum_{j \in \mathbb{Z}} x_0(j) g_0(n-2j) + \sum_{j \in \mathbb{Z}} x_1(j) g_1(n-2j).$$

To solve for $g_0(n)$ and $g_1(n)$ the equation $A(z)A^c(z) + B(z)B^c(z) = z^M$ is solved, wherein the solutions $A(z)$ and $B(z)$ are related to the values of the filter coefficients. The filter coefficients relating to the wavelet encryption system 13 of FIG. 1 are $g_0(n)$ and $g_1(n)$, with the z transforms of these coefficients being $G_0(z)$ and $G_1(z)$ respectively. Thus, each of the filter coefficients of the wavelet encryption system 13 and the wavelet decryption system 26 are related.

In fields with characteristic 2, M is an arbitrarily chosen even number less than or equal to N . Then above equation can be written as:

$$\{A(z) + z^{M/2}\} \{A(z) + z^{M/2}\}^c = B(z)B^c(z)$$

provided that $A(z)$ is a symmetric polynomial, $A(z) = A^c(z)$. Therefore, in this example, any $B(z)$ equal to $A(z) + z^{M/2}$ is also a symmetric polynomial. In summary, if M is an even number, the polynomial pair $A(z)$ and $A(z) + z^{M/2}$ is a solution to $A(z)A^c(z) + B(z)B^c(z) = z^M$ over $GF(2^r)$, where $A(z)$ is any arbitrary symmetric polynomial of degree M with a nonzero constant coefficient.

Based on the above, it will be appreciated that the polyphase components of $G_0(n)$ may be computed:

$$E_{00}(z) = A(z); \text{ and}$$

$$E_{01}(z) = A(z) + z^{(M/2)}$$

- 5 Using these polyphase components, $G_0(n)$ may be constructed using the equation $G_0(z) = E_{00}(z^2) + z^{-1}E_{01}(z^2)$. Because G_0 has been solved according to the abovementioned equations, coefficients $g_0(n)$, $g_1(n)$, $h_0(n)$ and $h_1(n)$ may be solved and the filters for the wavelet encryption system 13 and wavelet decryption system 26 matched, as will be appreciated by those of ordinary skill in the art. As noted
- 10 above, the above calculations may be implemented by hardware and/or software, and may be implemented, for instance, using a digital signal processing chip on the transmitting device 15 and/or receiving device 30.

Filter Derivation Method Two

- The first filter coefficient derivation method described above employs
- 15 symmetric polyphase filters to construct filter banks used in encrypting and decrypting plaintext and cyphertext, respectfully. This symmetry is very useful property to simplify the polyphase implementation of the filter banks and to reduce the number of additions and multiplications that are required by a wavelet cryptosystem according to the present invention. However, the symmetric structure
- 20 of the polyphase filters may reduce the strength of the security of the cryptosystem when it is used in a stream cipher mode. Therefore, as an alternative to the first method for deriving filters used in the cryptosystem, systems and methods of the present invention may alternatively utilize a second method that eliminates this security concern at the cost of slightly higher computational complexity.

- 25 It first should be appreciated that every filter bank has a polyphase matrix representation. To generate filters using the second method for filter derivation,

types of building blocks, $D(z)$ and $S(z)$, are assumed to be necessary and sufficient building blocks to construct two-band filter banks, where $D_v(z)$ is the degree-one PU building block defined by:

$$D(z) = d(0) + z^{-1}d(1) = I + l_v^{-1}v v^T + z^{-1}l_v^{-1}v v^T, \text{ where: } l_v = v^T v \neq 0.$$

5 It should also be appreciated that for two-band filter banks $v = [a \ b]^T$ is a vector of length two in $GF(2^r)$ and l_v is always square. The nonzero condition of l_v requires that $a \neq b$. A degree 2τ elementary building block has the following structure:

$$S_{\tau\zeta}(z) = \zeta(I + J) + z^{-\tau}I + z^{-2\tau}\zeta(I + J),$$

10 where $\zeta \neq 0$ is a scalar in $GF(2^r)$ and τ is any positive integer. Here, I and J are the identity and exchange matrices, respectively. Thus, $I + J = \begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix}$. Using the

second filter bank derivation method, to construct filter banks of a certain length several degree one and degree 2τ building blocks may be cascaded, where the order of the building blocks is arbitrary but where at least one degree one building block

15 is placed between each pair of degree 2τ building blocks. The product of these

building blocks results in a two by two polyphase matrix: $E(z) = \begin{bmatrix} E_{00}(z) & E_{01}(z) \\ E_{10}(z) & E_{11}(z) \end{bmatrix}$.

Having $E_{00}(z)$ and $E_{01}(z)$, $G_0(z)$ may be computed using the equation $G_0(z) = E_{00}(z^2) + z^{-1}E_{01}(z^2)$. Similarly, $G_1(z)$ may be computed using the equation $G_1(z) = E_{10}(z^2) + z^{-1}E_{11}(z^2)$. The filters of the synthesis bank $h_0(n)$ and $h_1(n)$ are then

20 generated from $H_0(n)$ and $H_1(n)$ as described above.

Next, the implementation of the wavelet encryption system **13** and wavelet decryption system **26** are discussed with respect to FIGS. 3-8. First, it should be appreciated that in a public key encryption system, user A sends an invoice to user

B, encrypting it via its secret key and user B's public key. The recipient (user B) then uses his or her private key and user A's public key to decrypt the transmitted document. One of the interesting properties of the finite-field wavelet is that it transforms the input data to a sequence similar to white noise. More precisely, 5 finite-field wavelets have a decorrelating property. Therefore, the encryption provided by the present invention is extremely difficult to decrypt or otherwise reconstruct.

In addition to this decorrelating property of the finite-field wavelets, there are two more key properties that the present invention exploits to construct a public 10 key encryption system. First, a high degree of non-linearity can be introduced by using nonlinear finite-field wavelets. Secondly, nonlinear wavelets have a unique structure that can be exploited to construct a public key encryption system with a very large key space.

As discussed above, according to one preferred embodiment of the present 15 invention encryption and decryption are performed by the synthesis and analysis banks, respectively, of the nonlinear finite-field wavelet transform. The cryptosystem is determined by the secret and public keys of the users. Thus, security is tied to the length of the wavelet basis function and to the nonlinearity within the wavelet transform.

20 According to a preferred embodiment of the present invention, systems of the present invention utilize wavelets that operate over $GF(256)$ and a nonlinear device that performs a mapping of field elements to their inverse in the field. Therefore, cracking a cryptosystem of the present invention using a chosen-ciphertext attack (in which the enemy is able to acquire an arbitrary number of 25 corresponding cipher and message pairs of his own choice) is equivalent to solving a set of nonlinear equations over finite fields. Additionally, as described above it

should be appreciated that the resulting cryptosystem can operate in either stream-cipher or block-cipher modes depending on whether the filter banks perform linear or circular convolution.

As stated above, the present invention utilizes the inverse wavelet transform
 5 for the encryption of the message and the wavelet transform for the decryption.

FIG. 3A shows an elementary transform block **45** that is used for encryption.

According to one aspect of the present invention, the elementary transform block
45 may be implemented by the wavelet encryption system **13**. It should be noted
 that the polyphase representation of the two-band filter banks (that are actually used
 10 in the implementation of the cryptosystem of the present invention) given by FIGS.
 3 and 4, are only valid if the first method of generating filter banks is used. Thus,
 the general well known polyphase representation introduced for real/complex fields
 should be used in case the system of the present invention employs the second
 method. Unlike the first filter derivation method, in this case, the polyphase
 15 representation is the same for both the finite field and real/complex field.

As illustrated in FIG. 3A, this elementary transform block **50** utilizes the
 inverse wavelet transform **45** together with a demultiplexer that splits the input
 signal $x(n)$ (e.g., plaintext) into even index $x_0(n)$ and odd index $x_1(n)$ sequences. If
 the first method for deriving the filter coefficients is used, the symmetric property
 20 of the polyphase filters may be exploited as noted above. The polyphase
 representation of multirate filters, as is known in the art, may be used to further
 simplify the structure of the transform block into FIG. 3B. In this polyphase
 representation **55**, $e_{00}(n)$ is the even index polyphase components of the filter $g_0(n)$.
 Using the first method for deriving the filter coefficients, and the assumptions used
 25 in the first method, the polyphase filter $e_{00}(n)$ can be any symmetric sequence of
 length $M + 1$, where M is an even number that is determined by the key length in

the cryptosystem, where the number of keys is $M/2 + 1$. This simplification reduces the number of operations by a factor of two because the length of the polyphase filter $e_{00}(n)$ is half of the length of the filter $g_0(n)$. The transform block maps the sequence $x(n)$ by a one-to-one mapping to the sequence $y(n)$.

5 The mapping that is performed by the transform block (TB) **50** is a linear and invertible transformation. By the property of the wavelet system, $x(n)$ (e.g., plaintext) can be extracted from $y(n)$ (e.g., cyphertext) by using the inverse transform block **70** shown in FIG. 4A. The inverse transform block consists of the wavelet transform **65** associated with the inverse wavelet transform in the

10 encryption block and a multiplexer that interleaves and combines the even and odd indexes to obtain $x(n)$. Similar to the transform block, the inverse transform block **70** defined over the field $GF(2')$ may be simplified as shown in FIG. 4B by the symmetric polyphase representation **75** having component $e_{00}(n)$ of the filter $g_0(n)$. In summary, FIGS. 3B and 4B as the basic blocks for encryption and decryption,

15 respectively. Therefore, the respective polyphase representations may be implemented by the wavelet encryption system **13** and wavelet decryption system **26**, respectively, of FIG. 1. It will also be appreciated with reference to FIGS. 3A, 3B, 4A and 4B that to determine the implementation of the encryption and decryption blocks, any arbitrary symmetric sequence $e_{00}(n)$ of length $M + 1$ may be

20 chosen, where M is any even number.

 In practical application, the cryptosystem of the present invention is set up such that both the transmitting device **15** and the receiving device **30** have the same filters. Next, two methods of effecting encryption and decryption based on the two methods of filter generations described earlier will be discussed. As will be

25 explained in greater detail below, a 128 bit key encryption results where the same 128 bit key (16 8-bit symbols in $GF(256)$) is generated twice. This may be

implemented by consecutive 64 bit encryption filters. After the consecutive 64-bit encryption filters produce a 128 bit key, coefficients of a second encryption round can be obtained by the permutation of the 16 symbols, as is well known in the art, to effect 256 bit encryption.

5 Key Generation Method One

The first method of filter generation is preferably used for the block cipher mode of the wavelet system. As noted above, to provide for encryption and decryption a symmetric sequence $e_{00}(n)$ must be generated in a secure way and provided to the transmitter and the receiver. To effect this the security of the
10 discrete log problem (DLP) over finite fields is exploited as described hereafter.

According to one aspect of the present invention, the transmitting device **15** and the receiving device **30** may each choose independently a symmetric sequence of length $M + 1$ as their secret key, where M is an even positive integer. For illustrative purposes, let the symmetric sequence $\{k_0, \dots, k_M\}$ be the secret key of
15 the transmitting device **15**. Additionally, let the symmetric sequence $\{\gamma_0, \dots, \gamma_M\}$ be the secret key of the receiving device **30**. Because the key is a symmetric sequence, the effective key length is $M/2 + 1$. The transmitting device **15** generates the public sequence by using the discrete log function over a cyclic group Z_p^* , where p is a large prime and it is such that the DLP is intractable over Z_p^* . In other
20 words, the transmitting device's **15** public sequence is the sequence $\{v_0, \dots, v_M\}$, where $v_i = \alpha^{k_i} \bmod P$. Here, α is the generator of the cyclic group Z_p^* . Since k_i are symmetric, the public key sequence $\{v_0, \dots, v_M\}$ is symmetric as well. Similarly, the receiving device **30** generates its public key sequence $\{\beta_0, \dots, \beta_M\}$ by using $\beta_i = \alpha^{\gamma_i} \bmod P$. If the transmitting device wishes to send a message to the receiving
25 device, the transmitting device generates a symmetric sequence by computing

$\beta_i^{k_i} \bmod P$ which is equal to $\alpha^{r_i k_i} \bmod P$ for $i=0, \dots, M$. This is a symmetric sequence that is used by the transmitting device 15 as the coefficient of the polyphase filter $e_{00}(n)$ in the encryption elementary block shown in FIG. 3B. Likewise, the receiving device 30 can compute its polyphase filter coefficients by combining the public key of the transmitting device with its secret key by using $v_i^{r_i} \bmod P$ which is equal to $\alpha^{r_i k_i} \bmod P$ for $i=0, \dots, M$. The receiving device uses the resulting symmetric sequence as the coefficient of the polyphase filter $e_{00}(n)$ in the decryption elementary block shown in FIG. 4B. This polyphase filter is the same as the polyphase filter that is used by the transmitting device 15. Therefore, the receiving device 30 can decrypt the ciphertext transmitted by the transmitting device 15. A third party cannot easily decrypt the message because it has to solve the discrete log problem in order to access the receiving device's 30 secret key.

Key Generation Method Two

The second method of filter generation, described in detail above, is preferred where a stream cipher mode of the wavelet system is used. Although this method can also be used for the block cipher method, it is not preferred for block cipher because it increases the computational complexity of the encryption and decryption. To generate 16 symbols key that are shared by the transmitter and receiver, a discrete log problem (DLP) may be used to implement the key exchange, as is well known in the art. Next, the generation of the polyphase filters will be explained (i.e., after the 16 key coefficients are determined by the DLP method in the devices 15, 30).

Where a first round consists of two sets of two-band filter banks, each filter bank uses 8 coefficients. This means that a polyphase matrix should have the following form $E(z) = D_{v1}(z)S_{2,\zeta1}(z)D_{v2}(z)S_{2,\zeta2}(z)D_{v3}(z)$ where the scalars ζ_1 , ζ_2 and

the vectors v_1, v_2, v_3 satisfy the criterion described above. Each vector v is specified by two key coefficients and each ζ is determined by one key coefficients.

Therefore, the total key usage to specify the polyphase matrix is 8. By this description, the lengths of the polyphase filters are equal to 8 as oppose to the previously described key generation method in which length 15 polyphase filters are required for each two-band filter banks.

Structure Of The Wavelet Encryption And Decryption Systems

According to a preferred embodiment of the present invention, the encryption and decryption systems **15, 30** of the present invention introduce nonlinearity to the wavelet transforms used to encrypt and decrypt information transmitted across the communication channel. Therefore, according to one aspect of the present invention, a nonlinear wavelet may be utilized in order to make the system resistant against security attacks. FIG. 5A shows an elementary nonlinear transform block **80** used for the encryption, according to one embodiment of the present invention. FIG. 5B shows an elementary nonlinear inverse transform block **90** used for the decryption, according to one embodiment of the present invention.

As shown in FIG. 5A, nonlinearity in the transform block is introduced by taking the output $y(n)$ of the wavelet system and passing it through a nonlinear operation **85** and adding the result to the incoming plaintext $x(n)$. The nonlinear operation **85** may be introduced by either raising the primitive element of the field $GF(256)$ to the power of $y(n-1)$ or by mapping of $y(n-1)$ to its inverse in $GF(256)$. Although either operations may be used, the mapping of $y(n-1)$ to its inverse in $GF(256)$ is used hereinafter as the nonlinear operation for purposes of illustration. Note that if the input $y(n-1)$ is a zero number it may be mapped to zero because a zero element does not have any inverse in $GF(256)$. The nonlinear inverse transform block **90** associated with the nonlinear transform block **80** is illustrated

by FIG. 5B, which also includes a nonlinear operation **95**. This nonlinear operation **95** is the same as the nonlinear operation **85** illustrated in FIG. 5A.

An overall proposed wavelet encryption system **100** implementing such nonlinearity is illustrated in FIG. 6A, and an overall proposed wavelet decryption system **120** is illustrated in FIG. 6B. As shown in the embodiment illustrated in FIG. 6A, the wavelet encryption system **100** consists of two rounds **105**, **110**. As explained in greater detail hereinafter, the two rounds **105**, **110** of the wavelet encryption system **100** may result in the total key size of 128 bits. It will be appreciated that the number of rounds may also be increased to reach a higher security level. These rounds **105**, **110** are identical except that the key in each round **105**, **110** is different from one another. Each round consists of two elementary blocks **80**, **50**. The first block is the nonlinear transform block **80** of FIG. 5A, though it is preferred that the transform block be implemented by its polyphase representation form. The second block **50** is the transform block **50** of FIG. 3A that may also be implemented by its polyphase representation **55** illustrated in FIG. 3B. According to one preferred embodiment of the present invention, each elementary block consists of the polyphase filter $e_{00}(n)$ of length 15 (for the second key generation method this length is 8) that operates over the finite field $GF(256)$. As discussed in detail above, the polyphase filter coefficients are the key unknown to a hacker attempting to intercept and decrypt an cyphertext transmitted from the wavelet encryption system **100** to the wavelet decryption system **120**. Because the polyphase filter is symmetric, the actual number for the key comprises eight coefficients in $GF(256)$, or equivalently 64 bits. Therefore, each round **105**, **110** of the wavelet encryption system **100** has key size of 128 bits. Additionally, the effective key size of the two-round wavelet is 128 because the key for the second round is obtained by the same 128 bits key of the first round by

some permutation of the coefficients, as is known to those of ordinary skill in the art.

FIG. 6B shows the wavelet decryption system **120** which consists of two rounds **115, 118** as in the wavelet encryption system **100**. Each round **115, 118** inverts the operation of the corresponding round **110, 105** of the encryption system **100**. Similar to the transform blocks of the encryption, the inverse transform blocks of the decryption system are preferably implemented by their polyphase form. As described above, systems of the present invention work in both stream cipher and block cipher modes via a simple change of the linear convolution to a cyclic convolution, respectively. Based on the filter length that is used, in the block cipher case, the length of the cyphertext block should be 30 symbols in $GF(256)$, or equivalently 240 bits. The number of additions and multiplications required by the convolution operation of the encryption and decryption process may be significantly reduced by using finite-field FFT or an appropriate bilinear cyclic convolution transform.

For higher security, it may be assumed that each time the system of the present invention initiates the encryption process, the initial states of the polyphase filters in the nonlinear transform block of the first round are chosen randomly. Because these initial random states are not used by the receiving device, the first block of the cyphertext will not be decryptable by the receiver. Therefore, in the block cipher mode, the first 240 bits will not be correctly inverted by the receiver (because the plaintext is added to the random initial state). Similarly, in the stream cipher mode, ciphertext of a length equal to the key size (128 bits) will not be decodable by the receiver if a random initial state is used for the polyphase filters of the nonlinear transform block in the first round.

As illustrated by the optional nonlinear operation illustrated in dashed lines in FIGS. 6A and 6B, to enhance the security of the cryptosystem an optional invertible nonlinear operation may also be used between the nonlinear transform block and the linear transform block at each round of encryption and decryption.

5 As an illustrative example, $(a)^{128}$ may be used as a nonlinear operator, where (a) is the input to the operator. This operation is invertible in the decryption rounds 115, 118 of FIG. 6B because $(a^{128})^2 = a$. Therefore, continuing with this illustrative example, $(a)^2$ could be used in between the blocks in the decryption rounds 115, 118 to reverse the effect of the nonlinear operation. As a result, nonlinearity can
10 further enhance the security of the system with little additional operations or expense.

For efficient implementation, the convolution operation may be performed for both block cipher and stream cipher modes in a cyclic fashion. This exploits fast (or less complex) algorithms to carry out the convolution. However, some parts of
15 the wavelet encryption system contain feedback which makes the cyclic convolution difficult to perform. To resolve this difficulty, the feedback system may be implemented in a block by block form. In other words, the output of the feedback system may be buffered for every block of size 240 bits. This block of the feedback output may be added to the next message block that will be encrypted.
20 In other words, the present feedback output does not affect the encryption of the current message. Instead, the current message is added to the feedback output (240 bits) resulting from the encryption of the previous message block. This way the cyclic convolution can be carried out naturally for the current data block that is under encryption process without the interference of the feedback output.

25 It should be appreciated that although in the above embodiments the inverse wavelet transform is used as the basic operation in the wavelet encryption system

13 and the wavelet transform is used as the basic operation in the wavelet decryption system **26**, the role of the wavelet transform and the inverse wavelet may be exchanged. In other words, as is shown in FIGS. 7A and 7B, the wavelet transform **124** in the basic nonlinear transform block **125** may be used to
5 implement the wavelet encryption system **13** and the inverse wavelet transform **128** in the basic inverse transform block **130** may be used to implement the wavelet decryption system **26**. Therefore, it will be appreciated that FIGS. 7A and 7B, respectively, show the structure of the nonlinear transform and inverse transform blocks when the roles of the wavelet and the inverse wavelet are reversed from the
10 preferred embodiment previously considered herein. It should be appreciated that a similar change may be applied for the linear transform and inverse transform blocks used in the wavelet encryption system and wavelet decryption system shown in FIGS. 6A and 6B.

Throughout the present description the invention has been described with
15 respect to two-band wavelet (i.e., two-channel filter bank) over finite fields to construct the wavelet encryption and wavelet decryption systems. However, as illustrated in FIG. 8, multi-band wavelets (i.e., multi-channel filter banks), which are the generalization of the two-band wavelets, may also be utilized to implement the wavelet encryption and decryption systems of the present invention. More
20 specifically, multi-channel filter banks forming an analysis bank **135** and a synthesis bank **140** are illustrated in FIG. 8. Therefore, cryptosystems of the present invention may also be constructed by multi-band wavelets (i.e., multi-channel filter banks). To further explain the implementation of this embodiment, the inverse wavelet (synthesis bank) of the two-band system shown in FIG. 5A may
25 be replaced with the inverse wavelet (synthesis bank) of the *M*-band system shown in FIG. 8. Similarly, the wavelet transform (analysis bank) of the two-band system

shown in FIG. 5B may be replaced with the wavelet transform (analysis bank) of the M -band system. Additionally, the message sequence $x(n)$ may be split into M subsequences as opposed to only two subsequences in FIG. 5. In other words, all the upsamples and downsamples by factor of two are replaced by the factor M . It
5 will be appreciated that similar modifications are required to construct the linear transform and inverse transform blocks if M -channel filter banks are used instead of the two-channel filter banks considered herein.

Many modifications and other embodiments of the inventions set forth herein will come to mind to one skilled in the art to which these inventions pertain
10 having the benefit of the teachings presented in the foregoing descriptions and the associated drawings. Thus, it will be appreciated by those of ordinary skill in the art that the present invention may be embodied in many forms and should not be limited to the embodiments described above. Therefore, it is to be understood that the inventions are not to be limited to the specific embodiments disclosed and that
15 modifications and other embodiments are intended to be included within the scope of the appended claims. Although specific terms are employed herein, they are used in a generic and descriptive sense only and not for purposes of limitation.